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Review

A Review of Power Co-Generation Technologies from Hybrid Offshore Wind and Wave Energy

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Abstract: Renewable energy resources such as offshore wind and wave energy are environmentally friendly and omnipresent. A hybrid offshore wind-wave energy system produces a more sustainable form of energy that is not only eco-friendly but also economical and efficient as compared to use of individual resources. The objective of this paper is to give a detailed review of co-generation technologies for hybrid offshore wind and wave energy. The proposed area of this review paper is based on the power conversions techniques, response coupling, control schemes for co-generation and complimentary generation, and colocation and integrated conversion systems. This paper aims to offer a systematic review to cover recent research and development of novel hybrid offshore wind-wave energy (HOWWE) systems. The current hybrid wind-wave energy structures lack efficiency due to their design and AC-DC-AC power conversion that need to be improved by applying an advanced control strategy. Thus, using different power conversion techniques and control system methodologies, the HOWWE structure can be improved and will be transferrable to the other hybrid models such as hybrid solar and wind energy. The state-of-the-art HOWWE systems are reviewed. Critical analysis of each method is performed to evaluate the best possible combination for development of a HOWWE system.

Keywords: hybrid offshore wind wave energy (HOWWE); distributed generation system; power take-off (PTO); tension leg platform (TLP); permanent magnetic synchronous generator (PMSG); maximum-power-point-tracking (MPPT); doubly fed-induction-generator (DFIG); voltage source converter (VSC); linear generator (LG)

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1. Introduction

According to the contemporary scientific research, around 78–80% of the world's electricity used for commercial purposes is produced from fossil fuels [1]. However, there are many negative effects on the environment due to high carbon sources, such as affected rain and air. In light of this, the countries around the world have been consciously transferred to use of low-carbon energy sources. Energy production from wind-wave energy, tidal power, solar-PV energy and biomass are copious sources that can harvest affordable and clean energy. Offshore wind-wave energy are plentiful resources, which can be exploited without compromising the needs for future energy. Hybrid offshore wind and wave energy (HOWWE) is measured as an innovative technology for producing electricity due to its abundant availability of both winds and sea waves at one same location.

This review paper purposes the progress of HOWWE in the world and signifies important phases to be engaged for its influence on the net-zero target by 2050 in the UK. The UK has outstanding wave energy resources and progressive methods that are essential to be promptly advanced to attain the target of 22 GW by 2050 [2]. The UK has the prospective to produce electricity over 48 GW from offshore wind energy by 2050 [3]. The growth of HOWWE systems in the world are also studied and defined to highlight the significant support in obtaining net zero target. It is evident that HOWWE can contribute to the de-carbonization, thus helping to attain net zero target.

The benefit of power production from HOWWE is because electricity can be generated from both wind and wave with high capacity. Power can be generated from mixture of the numerous offshore-wind turbines and wave generators, as called a HOWWE-farm. They can be offshore wind-wave jointly or separate offshore wind turbine and wave energy devices complementarily. Therefore, there is same grid to use this output energy. There are some practices applied for HOWWE to certify output-power, stability and grid interconnection.

The research and development of the HOWWE has practically experienced productive and significant progress over the past two decades. The hybrid system has a prodigious potential for improvement and creates a vital part in the EU and global energy policy [4]. The worldwide target capacity of 460 GW offshore-wind and 188 GW wave-energy has been established by 2050 [5]. HOWWE has received increasing interests recently because of being more eco-friendly, rising of the global warming, and decreasing natural resources [6,7]. The wind speeds at sea tend to be faster than on land. The waves are a reliable source of energy due to continuous motions of sea waves. The system is area efficient due to power integration from both wind and wave energy resources at one location [8]. The connection to the electric grid can be made by the same cables for HOWWE device [9]. This would provide a continuous power supply, low maintenance cost, and environmentally friendly and cost-effective energy sources [7].

The review paper covers all possible primary aspects of the HOWWE. The paper starts with the brief explanation of the power conversions of offshore-wind, wave-energy and the power conversion from HOWWE. For the offshore-wind power conversion, different generators and their working principle are covered, while for the wave power conversion, different PTO systems are analyzed with sea wave interactions. It is noted that the distributed generation system comprising wind, wave, solar and hydro-power has also received the increasing attentions. The advanced power conversion techniques by using phase locked loop (PLL) based inverter can improve the efficiency of such systems since the PLL based inverter can be an excellent choice for combining the DC output from multiple sources such as HOWWE.

This paper will review the response coupling of HOWWE such as the system combing a spar type floating-wind-turbine (FWT) and point absorber converter. We will present the control scheme for co-generation and complimentary generation form wind and wave by analyzing their positive and negative aspects, respectively. The colocation deployment is a feasible solution to maximize the energy output from both resources by selecting a suitable location and therefore different approaches for site selection of HOWWE are also reviewed. We will also review the integration of the HOWWE system, covering integration methodologies, designs, structures and farm types.

This review article is organized as follows. Section 2 presents the power conversion of the HOWWE system. Section 3 classifies the response coupling of HOWWE where spar torus wind-wave floating systems are discussed as the examples. The control scheme for co-generation and complimentary generation is presented in Section 4 while the colocation of HOWWE is presented in Section 5. Section 6 reviews the possible integration methodologies followed by synergies and recommendations for future developments in Section 7.

2. Power Conversion

2.1. Offshore Wind

Power conversion is the key part of the wind turbine used to change mechanical rotations into electrical power-energy to meet regulations of voltage and current [10]. The purpose of power conversion is to convert the intermittent winds to a power output with controllable magnitude and frequency. A detailed review of power conversion of offshore wind is presented in [11]. Wind power needs to provide continuous maximum power by implementing maximum-power-point-tracking (MPPT) technologies. The challenges and prospects facing the power conversion system of offshore wind are discussed in [12]. The usage of power-converters is attractive to build efficient power while working in harsh conditions. In this manner, power circuits are probably going to supplant the silicon-based power switches [13], which will not just offer high unwavering quality due to high temperature. The evaluation of converters in enormous scopes essentially relies upon the type of generators utilized. In doubly fed induction generators (DFIGs), rotor-side-converter (RSC) and grid-side-converter (GSC) are utilized to interface the rotor-circuit using slip-rings to the grid.

Both permanent-magnetic-synchronous-generator (PMSG) and DFIG deal with the capacity of reactive and real power control, dispensing with the requirement for reactive power [14]. The RSC is ordinarily to regulate the reactive-active power of the generator, while the GSC is utilized to retain with the DC link voltage [15]. The voltage-source-converter (VSC) gives speed adaptability with PMSG. With regard to the power transmission, the VSC with high voltage direct current (HVDC) has been developed as an attractive method for the long-transmission of offshore-wind. The VSC HVDC has taken over the HVAC transmission system in offshore sectors because HVDC system is more efficient for transferring power over long distance [16]. The numerous upcoming choices are discussed in [17] to upsurge offshore wind power by minimizing investment and repairing expenses for such power conversion solutions. The power conversion can implement MPPT and hence regulate voltage and frequency control. The offshore wind power conversion system has become a reliable HOWWE part for electric power generation.

An example of wind turbine and its connection to the grid are shown in Figure 1. Learning about offshore wind generators is a necessity for grid connection because numerous generators are selected and each generator type has a unique interconnection system. The wind energy industry makes extensive use of induction generators. The first wind turbines were powered by squirrel cage generators, which were grid connection directly using full-rated-power converters operating at varying speeds. When wind turbine generators are first connected, there may be mechanical stress and inrush current. A soft starter made of thyristor equipped electronics was employed to address this issue. Induction generators need reactive-power from the grid, which lowers the power quality by causing voltage drops or low power factors. Switched capacitor banks or specially built power converters can be used for power factor correction. Reactive power can be supplied by switching capacitor banks for fixed speed generators to increase power factor, and back-to-back power converters for variable-speed induction-generators to reduce reactive power and raise power factor. With the capacitor bank, the soft starter is frequently used with squirrel cage induction generators (SCIG). With technological advancements, the evaluation of generators used in offshore wind power generation changes. Due to the significant reactive-power consumption that requires essential compensation, SCIG was substituted. In demand to fulfill power electronics interface with the rotor currents, the DFIG, a type of variable speed wind turbine, was invented, which is connected to the grid using a power electronics converter. The generators are composed of a rotor and a stator, which work based on the theory of Faraday's law of electromagnetic induction.

Through slip rings, the power source is connected to the rotor's magnetic field, and the stator's three phase windings are separated. Rotor speed for synchronous generators is influenced by operating frequency and the number of magnetic poles. Wind turbines typically have a tip speed ratio of 6 to 8, which requires a generator speed of 100 to 500 rpm. As more poles are needed to attain a low rpm speed, the cost of the generator rises. Using a gearbox is another way to match the generator's speed since it enables the rotor blades' low speed to meet the generator's high speed. As compared to the DFIG and SCIG, the PMSG is an ideal choice for offshore wind power production due to the positive aspects such as gearless transmission, low cost of maintenance, and high reliability with ease of power conversion control. The likings of PMSG for HOWWE comprise exceptionally different speed ranges and improved efficiency from SCIG and DFIG, as shown in Figure 1. It has a great power density due to use of earth based rare permanent magnets, which is suitable for a compact design within the HOWWE energy system. The advantages and disadvantages of different wind generators with respective conversion system are given in Table 1.

Table 1. The advantages and disadvantages of different wind generators with respective conversion system [17].

Wind Turbine Generators	Advantages	Disadvantages
Fixed speed induction generator	Maximum power production is possible	Minor variation in speed can cause large-torque. Difficult to control the generator torque. Aerodynamic fluctuation is moved to the grid side causing grid faults. High power-driven stress and power losses.
DFIG with partially rated power converter	Torque of generator is entirely under control of the power conversion. Speed can be improved by 40%, therefore MPPT is achievable. Very rapid torque control, response time of the torque is from 5 to 50 ms. Aerodynamic fluctuation can be filtered before entering the generator.	Magnetizing current is delivered via the rotor terminal affecting loss of efficiency. High maintenance requirements of slip rings. Aerodynamic fluctuations may cause grid faults. As with PMSG, power-converters are required to connect the grid.
PMSG with fully rated power converter	Voltage and reactive-power control are accessible to the grid without upsetting the dynamics of generator. Gearbox can be avoided.	PMSG cannot be straight joined to the grid. Power conversion is required between the generator and the grid.

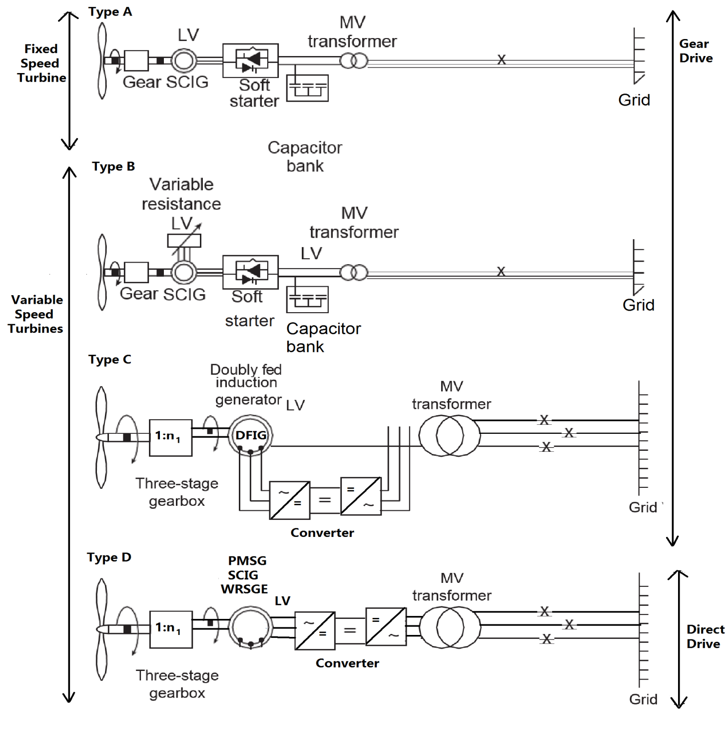

Figure 1. Power conversion of PMSG, DFIG and SCIG wind turbines, (**A**) the SCIG fixed speed generator with gearbox, (**B**) SCIG variable speed coupled with a gearbox, (**C**) DFIG with the partially rated power converter, and (**D**) direct-drive PMSG with fully rated power converter. Adapted with permission from Ref. [18]. 2012, IET.

According to the survey [19], 42% of ongoing WECs utilize water-powered PTO while 58% WECs from linear generator. The hydraulic-PTO is a system intended to transfer the oils to the accumulator and cylinders. The device incorporates rams or cylinders which can change the mechanical energy from the movement of the oscillating body into hydraulic energy. The pneumatic-PTO uses the development of caught air prepared by the process and drives a regular air turbine. The pneumatic PTO is exchanged with a conventional connection between the airflow rate and the OWC pressure [20]. There are three air turbines used in the OWC devices, including well, Denniss-Auld turbine and impulse turbines.

2.2. Wave Energy

The power takeoff (PTO) of a WEC (Wave Energy Converter) is used to extract wave power and transform it into the useable electricity. The following types are used for power generation from wave energy by combining the offshore wind turbine. Mainly, there are six types of WECs such as point absorber, rotating mass system de-vice, oscillating water column (OWC), terminators, submerged pressure differential device, and attenuators. While sharing the same structure for combining wind and wave energy resources, point absorber might be an ideal choice because it is attached with the bottom part of tripod offshore wind turbine. The OWC device is ideal for the hybrid system if WEC arrays are added separately with the offshore wind platform. The OWC moves up and down due to sea waves, in response to the air which comes out from the chamber and pushes the chamber back into its position. The high-velocity air is produced due to the repeating processes of the reversing stream. These systems appear simpler and more reliable than the other system such as rotating mass device. In the OWC air turbine, there has no moving parts. These systems are suited for any type of environments such as offshore, shoreline and near the shoreline. The PTO is utilized to change the ocean wave power into electrical energy, which is represented in Figure 2, where the PTO is categorized into hydraulic, pneumatic, hydro and direct drive system incorporating an appropriate electric generator such as the linear gener-ator, respectively. A comprehensive PTO study of the wave energy system is carried out in [18]. According to the survey [19], 42% of ongoing WECs uti-lize water-powered PTO while 58% WECs from linear generator. The hydraulic-PTO is a system intended to transfer the oils to the accumulator and cylinders. The device in-corporates rams or cylinders which can change the mechanical energy from the movement of the oscillating body into hydraulic energy. The pneumatic-PTO uses the development of caught air prepared by the process and drives a regular air turbine. The pneumatic PTO is exchanged with a conventional connection between the airflow rate and the OWC pressure [20]. There are three air turbines used in the OWC de-vices, including well, Denniss-Auld turbine and impulse turbines.

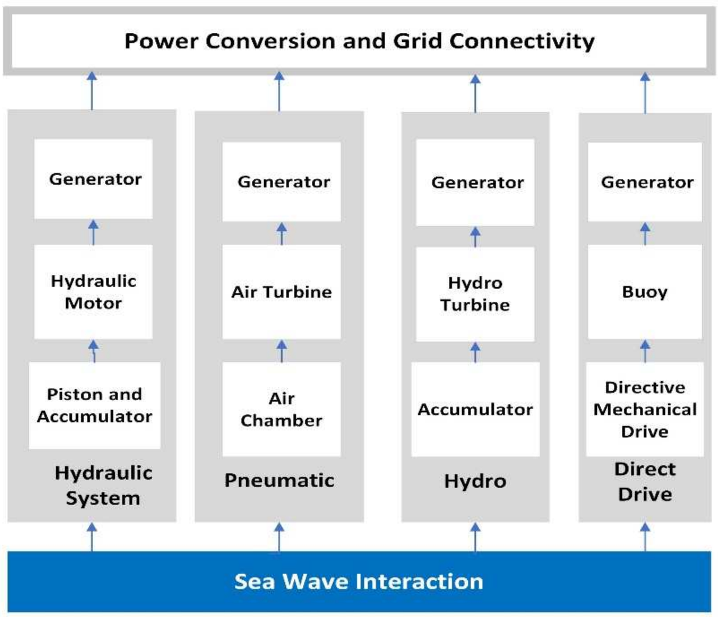

Figure 2. Typical PTO systems used in the wave energy devices.

The hydro-PTO devices are generally utilized in over-topping converters such as impulse turbines. The direct-drive PTO straightforwardly associates with the major mover through mechanical linkages (e.g., gearbox, clutch, belt pulley and grasp components). The WEC with linear generator is simpler and less expensive for power yield. There are two types of generators that are utilized in WECs: linear and rotatory generators [21]. In wave energy, the linear generators are most likely thriving because of their high energy density and more effectiveness at low speeds. The linear generator can be straightforwardly joined to a vertical chamber, which is regularly utilized in the oscillating systems [22]. In [23], WEC PTO is based on a drive train technology by using linear Vernier and the experiment is carried out using a direct drive machine with 3-dimensional finite element technique. There is an alternative solution that joins two drive train technologies such as the linear Vernier hybrid permanent magnet machine coupled with a magnetic gear. A unique bistable X-structured WEC is proposed and examined in [24]. The sea waves drive the buoy to up and down, and due to the moment of buoy the base excitation is produced for the supporting X-structure, which produces the relative motion to generate electricity [24].

2.3. Power Conversion of HOWWE

The power conversion is a crucial part to improve the stability of the HOWWE system. The power output from HOWWE is harvested separately, i.e., wind power conversion is carried out using AC-DC-AC conversion by using control algorithms and MPPT techniques while wave power conversion is made based on PTO and the associated conversion process. The detailed power conversion from offshore wind and wave energy is investigated in [25]. The power integration based on offshore wind power and wave energy (W2P) is presented in [26]. A HOWWE system based on hywind and wavestar is presented in [27]. In [28], the prospects of combining HOWWE for a commercial purpose and approaches used to mitigate fluctuation effects with this combination are discussed. It was reported from [29] that the power output efficiency from offshore wind energy can range from 30% to 50% from winds while power output from wave energy can range from 22% to 29% from waves. A micro-grid based on offshore wind and wave energy resources is presented in [30], which is fed to an onshore grid system based on VSC. A hybrid wind-wave system is also proposed and used in a DC microgrid [31]. As shown in Figure 3, the hybrid system is designed in an integrated manner by which the hybrid power generation system is connected into the bidirectional DC microgrid that is operating in an islanded mode. The AC grid is connected with the bi-directional grid-tie inverter with the PMSG and linear permanent magnetic generator (LPMG) being used, respectively. The coupling between the linear generators with Archimedes wave swing (AWS) based WEC system was compared using a 2 MW system in [31].

To optimize power-sharing in DC micro-grid from wind and wave, the voltage DC-link is developed and shared in the micro-grid by using VSC control strategies [30]. To find the maximum energy needs between the battery and capacitor, an efficient power converter is required. The DC-DC bi-directional converter was therefore proposed to integrate the wind and wave with intermittent and uncertainty features [31]. The hybrid system is connected to the DC grid through PMSG-VSC and LPMG-VSC. The resistive load is linked to DC micro-grid through a DC-DC converter. In [31], both DC and AC micro grids are also discussed. To attain load demand and steady power of the DC grid, a battery is connected through a bi-directional grid-tied inverter [32]. The HOWWE power is fed into the DC micro-grid with the charged batteries and this surplus power is delivered to the AC grid by the inverter. Indeed, merging two resources increases the power output of a renewable system such as the hybrid wind and solar [33,34]. Hybrid renewable energy systems and their applications based on wind and solar are presented in [35,36] to enhance the microgrids by integrating renewable resources. The smooth output power of HOWWE and minimum downtime period from both wind and wave farms are presented in [37,38]. Similarly, the farm layout structure is also important for power conversions; the co-located farms could produce enhanced power output from both resources in an easy maintenance and cost-competitive way. Although there is growing importance in co-exploiting renewable resources from offshore wind and wave [39], HOWWE exploitation has faced a number of challenges such as cost, risk and complexity, which are addressed in [40].

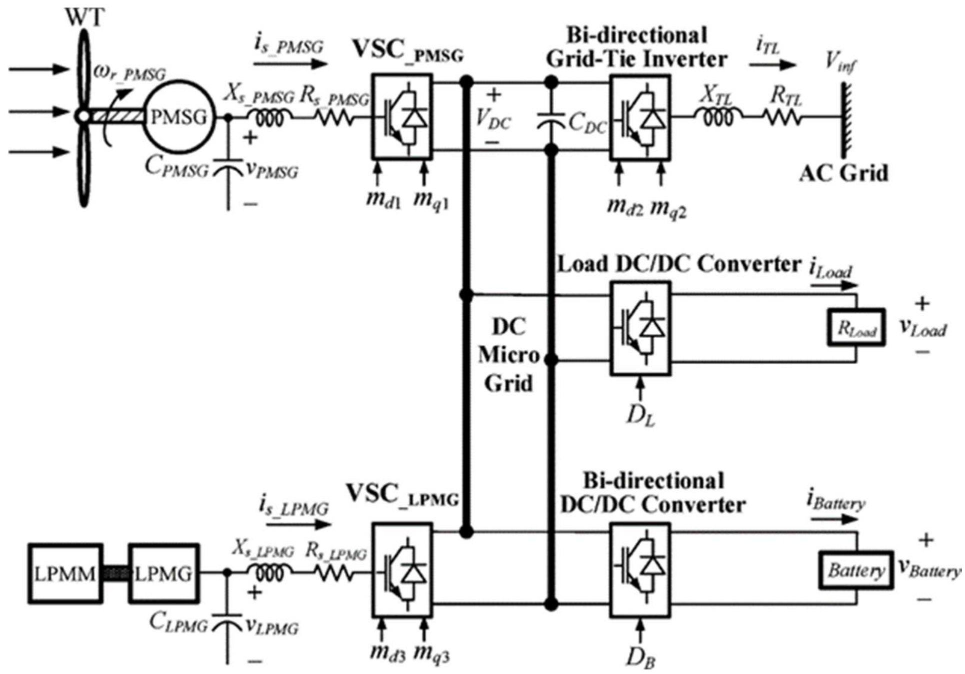

Figure 3. Schematic of a hybrid wind-wave energy system for DC power supply. Reprinted with permission from Ref. [31]. 2015, IEEE.

3. Response Coupling of HOWWE

Response coupling is an integral part of the HOWWE system. It not only involves current and voltage regulations but also deals with power flow control and structural protection. The HOWWE capacities are usually investigated by wind and wave models, where the atmosphere wave ocean (AWO) dynamical coupling methods are ignored [41]. The AWO coupling control methods for the simulation of HOWWE potentials are examined using a fully AWO coupled model. Similarly, the synergies and coupling between wave energy and wind are investigated in [42]. With regard to the coupled dynamic analysis methods, an analysis is performed in [43] to use a WEC as a motion suppression device for FWTs, which employs the passive damping technique for FWTs to dissipate the wave-induced energy, thus reducing the global platform motions. SIMO-RIFLEX-AeroDyn, an aero-hydro-servo-elastic simulation tool, is used in [44] for real time hybrid model testing. The aerodynamic loads on the FWT in a wave basin is also investigated based on simultaneous simulations by the authors in [44]. Simplified FWT models are also investigated by a dynamic link library called TDHMill (Thrust-Dynamic-Horizontal-Mill) to define aerodynamic loads. This approach has been used to compute the aerodynamic loads through the mapping of steady-state aerodynamic coefficients [45]. One of the key features of this approach is that analysis time is significantly faster than that of standard codes and results are accurate in conditions where rotor dynamic is not considered.

A novel joint wind-wave energy (JWWE) power conversion system is proposed in [46], where a dual-stator linear and rotary permanent magnet generator (DSLRPMG) is deployed to convert the wave and wind energy, respectively. The joint offshore wind and wave energy power conversion is directly employed to convert mechanical energy to electrical energy. The DSLRPMG system can be deduced by using the vector control method. The flux and power decoupling method are proposed, as shown in Figure 4, where the linear and rotary motions of the DSLRPMG magnetic field presents strong coupling effects. Since the back electromotive force and flux linkage are both sinusoidal, by ignoring the magnetic saturation, hysteresis loss and influence of the temperature, the linear motion v_1 and rotary motion ω_r are expressed by the equations below [46].

$$\begin{array}{l} T_L = J\frac{d\omega_r}{dt} + B_r\omega_r + T_e \\ F_L = M\frac{dv_1}{dt} + B_1 v_1 + F_e \end{array} \quad (1)$$

where F_L is input torque of the linear motion and T_L is the input torque of rotary motion. J represents the rotary inertia and M represent the mover weight. T_e is the electromagnetic torque and F_e is the thrust of the DSLRPMG. The coefficient of transmission friction of rotary and linear parts is represented by B_r and B_1, respectively.

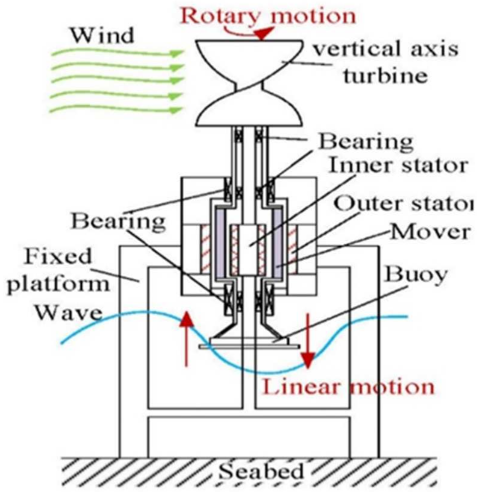

Figure 4. Coupling of the hybrid wind and wave energy conversion. Reprinted with permission from Ref. [46]. 2020, IET.

In [47], the OWC type WEC is combined with the monopole wind turbine. The main formation is to integrate a monopole with cylindrical OWC chamber. The chamber is attached to the offshore monopole turbine, unconstrained at the base and linked at the top part to a wind turbine. In [37], a cost-effective solution is provided by combining the floating wind and WECs, to improve size and design of WECs in the system by which the larger WECs generate more energy in a specified area. In [48], a numerical model is tested to find rational size of the HOWWE. By studying different PTO structures in the hydrodynamic model and their influence on WEC performance under different conditions, finest damping coefficient is achieved.

In the work [48], hydrodynamic performance is mathematically examined and then evaluated experimentally with a monopole offshore wind turbine (OWT) being integrated to the OWCs. The linear potential flow theory in a 3D time-domain is numerically developed. In [49], the structure shape of OWC is coaxial cylindrical cylinder with two parts. The internal cylinder signifies the OWT mono-pile while the outer cylinder has a skirt whose range is to monitor the wave energy flux. In [50], an innovative HOWWE system is proposed and the initial feasibility study of both FWT and OWCs is achieved by applying numerical simulation of aero-hydro-servo-mooring. The significant impacts of the WEC PTO system on the hybrid system are also studied.

In [51], a combined HOWWE model comprising a 5 MW FWT is coupled with a torus-type WEC and examined by four different WEC shapes. The dynamic study of the tension leg platform (TLP) for offshore wind with point absorber WEC is examined. In [52], joint coupling between spar-type FWTs and torus-shaped WECs is investigated. Numerical simulations of the coupled HOWWE with a positive synergy between spar floating wind and WEC under operational conditions are presented in [53,54]. A floating system is proposed which contains an array of hydrodynamically interrelating OWC devices, moored into TLP, and supports a 10 MW wind turbine [55]. The hybrid platforms are proposed in [48,56] with the WECs positioned at downwind and upwind directions being analyzed to study the system stabilization problem. The time and frequency domain analysis for a point absorber is carried out to measure the non-linear dynamic responses in [57,58]. Similarly, in [59], a point absorber array is connected on a three-pontoon semi-submersible system and a prototypical experiment is then carried out. A numerical model is designed for optimization of the size of wave energy installations in HOWWE system in [60]. The existing wind-wave coupling models are summarized as follows [61].

3.1. Spar Torus Combination (STC)

For the STC, the parts such as spar, torus and wind turbine are usually rigid bodies and mooring lines are represented by linear springs. The wind turbine acts based on the aerodynamic load while the spar acts based on hydrodynamic loads as with the drag force and first-order wave loads. The numerical modelling of the two models regarding the STC and the semi-submersible flap combination (SFC) is studied in [62]. The comparison is carried out between numerical and experimental results for both STC and SFC. The excitation of wind and wave energy model is tested at a 50:1 scale, where the HOWWE conversion is achieved using the STC. The floating spar type wind turbine combined with point absorber WEC is reported in [63]. In this configuration, the point absorber WEC is slid across the spar to extract energy from waves while at the same time the FWT extracts energy from winds. This is a comparatively simple and stable model and thus understandingly presents many feasibility problems. However, the current system still has the potential to achieve the maximum performance. Moreover, this system needs to be designed for fatigue limit test and ultimate limit test in the operation mode. Figure 5 shows the detailed numerical analysis model of STC conceptual sketch with different survival modes [64].

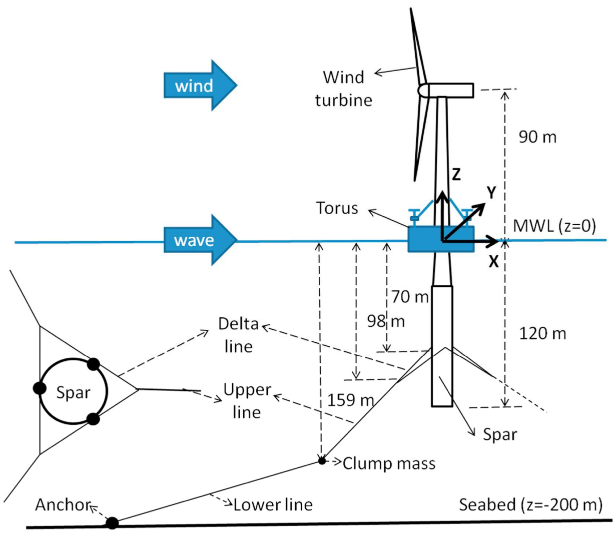

Figure 5. Spar torus combination conceptual sketch. Adapted with permission from Ref. [64]. 2015, Elsevier.

3.2. Wind Wave Float

Different hybrid wind-wave floating systems are presented in [65]. A hybrid system is proposed with a tri-floater wind turbine and point absorber WECs [66]. This model generates energy by exploiting the oscillation of moving flaps, which has received more attentions in recent years. The basic functions of sea wave spectra produced by winds and waves reveal a typical plus-minus mark related to change of the severe spectral peak to minimum frequencies [67]. The power performance from combination of FWT with WEC is studied in [68]. In [69], a unified method for the Froude scale model is tested for FWTs under HOWWE load distribution. The indication of the Froud scaling interactions engaged for the location and floater is presented. Subsequently, an argument is accessible regarding recommended approaches for working Froude scale wind turbine setting in a wave basin to ease the application of the HOWWE model. For an array of FWTs, the stand motions and fatigue damage due to wind-wave misalignment effects are examined under typical operative circumstances. The dynamic floating wind-wave effect is fully examined using the innovative geometrically scaled National Renewable Energy Laboratory (NREL) wind turbine of 5 MW at top three floating platforms, i.e., a TLP, a spar-buoy, and a semisubmersible, to demonstrate the application [70].

4. Control Scheme for Co-Generation and Complimentary Generation

In HOWWE, to reduce the fatigue of the wind turbine independent blade pitch controller is used to manipulate the blades independently [71,72]. The multi-blade coordinate is investigated in [73], where the fixed coordinate system is made based on cosine-cyclic, sine cyclic and collective coordinates. The individual pitch control is used to minimize the wind torque fluctuation. However, it is difficult to implement a control scheme to guarantee both efficiency and reliability simultaneously because these two requirements involve conflicting objectives [73].

Since incoming wind is stochastic, to estimate the unknown system and the disturbance state of the system it is compulsory to use output measurements. The wind speed variation, un-modelled dynamics and nonlinearity are checked by using the different control schemes. A disturbance accommodating controller is used for checking and adjusting the rotational speed of the turbine rotor for a variable-speed turbine [74,75]. To stabilize the system with unknown exogenous disturbance and un-modelled dynamics a stochastic disturbance accommodating controller is also presented in [76]. The ability to cancel the disturbance can be made by using a modified direct model reference accommodating controller [77].

The output power of the HOWWE system can be tracked by using controllers, which determines the maximum aerodynamic efficiency. It is hard to find maximum power coefficient between the blade pitch angle and a tip speed ratio of the non-linear function. The MPPT will improve the output power efficiency by tracking the optimum aerodynamic torque by using the conventional MPPT including perturb and observe, optimal torque, and tip speed ratio control. The MPPT algorithms based on the optimal power coefficient of the system can be referred in [78]. As an example, the nonlinear sliding mode control is used to optimize output power for variable DFIG turbine [79]. The system is implemented based on two controllers, with a control loop tracking the rotor speed and another controller tracking the rotor flux and generator torque. The power optimization can also be achieved by manipulating the generator toque through the Lyapunov controller and the optimal-direct-shooting control method [80].

5. Colocation of HOWWE

The HOWWE co-location is robust as compared to hybrid wind and solar energy due to energy harvesting on one platform. The HOWWE is the advanced type as compared to other marine energy resources in terms of the infrastructure policies, industrial manufacturing, worldwide commercialization, installed capacity and technical improvement. The interest is to find an efficient HOWWE solution by tuning the parameters of a wind turbine such as large rotors and wave generator with efficient mechanical and electrical design interaction along with the water depth [81]. A complete analysis of HOWWE colocation between wind and wave has been proposed by several researchers [82,83]. The improved output power from combined energy resources using minimum cost structural design is presented in [84,85]. The HOWWE has been examined in the Mediterranean region by [86] and in Italian [63]. In Table 2, different site locations are discussed where the potential deployment of the HOWWE are evaluated and tested.

Table 2. The site location of HOWWE.

Wind-Wave Resources	Sea	Coasts and Islands
Europe	The Mediterranean	The French-Blue-Coast, Sicily and Tunisia and Greek-islands [63]
	North-Baltic	The North Scottish-islands, Norway South-West part Denmark-West-coast [87]
	The North-East-Atlantic	Atlantic Arc
UK	Celtic Sea	Celtic sea power [85]
	Irish-Sea bounded Scotland	Danish outfit Floating Power Plant
China	South China Sea	Paracel Islands

According to EEA (EEA European Environment Agency) [87], offshore wind for energy production potential in the Mediterranean is at 20%, Baltic at 29% and the North Sea at 25% by 2030 of approximately 7100 TWh covering these areas. There are heavy investments in HOWWE in the Baltic and North Sea. Concerning the wave energy, the low power density (~5 kW/m) is characterized in the Baltic Sea, Mediterranean Sea and the Black Sea due to the short period of waves [88]. The HOWWE in the China Sea was checked from 1988 to 2009 by using a third-generation wave model. The third-generation wave model predicts wave climates in offshore and coastal areas [89]. The geographic information systems are used for pairwise comparisons of each resource in [37]. The annual wave energy was found from 8.46–12.75 kW/m and mean wind power density is from 0.08–0.16 kW/m^2 in the Maldives [90]. In the Mediterranean Sea, there are low resources of HOWWE; therefore, the most suitable energy resources for both wind-waves are in the Baltic and Northern seas. Based on wind-wave speeds and their forecast data, for the combined exploitation, the best areas are situated in the Aegean Sea north east coasts, Gulf of Loins, coasts of Sardinia and in the Sicily Straits [63,87].

5.1. Statistical Methods for Correlation

The leading concern when applying offshore wind and wave resources is their inconsistency and intermittency. The correlation of HOWWE in deeper waters as compared to closed basins and semi-closed open areas is discussed in [91]. At different locations the HOWWE correlation is described by Pearson's coefficient r [6]:

$$r = \frac{1}{N}\sum_{k=1}^{N}\frac{[x(k)-\mu_x][y(k)-\mu_y]}{\sigma_x\sigma_y} \tag{2}$$

where the total number of samples is N, μ_x μ_y are mean value of observations x and y, and σ_x and σ_y are their standard deviation, respectively. The cluster-analysis (CA), factor-analysis (FA) and principal-component-analysis (PCA) have been required to minimize the Meteo-climate datasets in the aspect of dimensionality reduction for feature extraction [6]. Among them, the PCA and FA appear the most suitable choice to minimize the dimensionality by extracting the eigenvectors and eigenvalues from the covariance matrix. The groups of Meteo-climatic data are also analyzed by CA, which has k means of hierarchical and non-hierarchical control.

5.2. Site Selection

To find an appropriate site location for HOWWE, the offshore wind is calculated by Bulk aerodynamic method that is based on the 10 m standard height with the shift of wind measurements. This height is used because the height of the anemometer results in increase in the chattering level of wind turbine, thus causing un-stability [37]. The accurate offshore wind speed can be derived by a power law and is expressed by Equations (3) and (4) [92].

$$\frac{U_{10}}{U_2} = \left(\frac{z_{10}}{z_2}\right)^{\in} \tag{3}$$

where the U_{10} and U_2 refer to the speed of wind at height of 10 m and 2 m, respectively. The wind shear exponent is symbolically represented by $\in$ and is expressed as:

$$\in = \frac{1}{ln\left(\frac{z_{10}}{z_0}\right)} \tag{4}$$

where z_0 to z_{10} depend on the wave characteristics and represent the aerodynamics roughness-length.

In Table 3, site selection based on northern and southern hemispheres are presented for offshore-wind and wave-energy, respectively.

Table 3. The HOWWE distribution in the northern hemisphere's degree (40°) and in the southern hemisphere's degree (60°).

Worldwide Zones	Offshore Wind	Wave Energy
North Hemispheres	European Atlantic coast [87], US, Greece, China [37], and Japan	European Atlantic coast [87], Iceland, Greenland, United States, Coasts of Canada [93]
South Hemispheres	Southern part of New Zealand, Chile, Kerguelen, the Heard Island and McDonald Islands	Australia, New Zealand, Western coast of South-America [93]

6. Integrated Conversion System

According to the technology development, the system can be categorized in terms of water depth (deep water, transitional, and shallow-water waves) and the location near to the shoreline (offshore, near-shore, shoreline). The system can also be classified according to its connectivity. The hybrid connectivity between FWT and WECs can be made via hybrid, co-located and island system modes. Furthermore, the co-located system can be considered as the bottom-fixed and floating-system. The integration of wind-wave energy using co-located array with grid management system is discussed in [94]. The independent and combined arrays are the two categories of co-located systems. The representative structural designs of the co-located HOWWE are presented in Figure 6. The independent separate arrays are presented based on separate FWT and WECs [8]. The combined arrays are proposed of the co-located offshore wind and wave devices at the same farm, sharing the same ocean area and the other infrastructures, to form a single array [29]. Moreover, the combined arrays of co-located systems are divided into three sub-types, namely peripherally distributed-array (PDA), non-uniformly distributed-array (NDA) and uniformly-distributed-array (UDA).

In the PDA, the WECs are distributed as per the prevailing wave direction while in UDA the WECs and offshore wind turbines are geometrically distributed uniformly. In the NDA arrangement, the WECs are geometrically distributed non-uniformly throughout the offshore wind farm. The best method of the distribution array among them is NDA because this arrangement is able to maximize the WECs performance by interacting with the wind turbines.

The offshore structures are merged by different marines, like offshore wind, aquaculture, marine leisure and transport [95]. Based on their installation, the hybrid systems are classified into floating hybrid and bottom fixed systems. For the bottom fixed system, the structure is developed by utilizing offshore wind turbine to adjust the WECs.

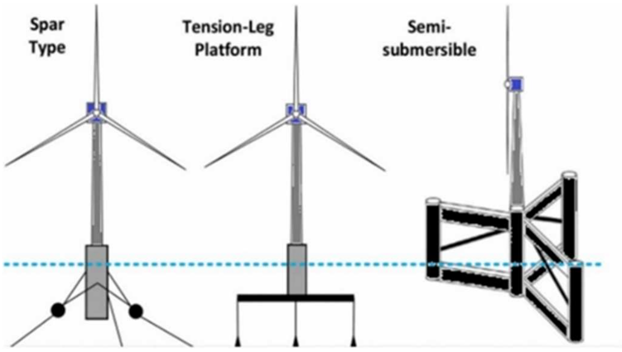

Figure 6. Spar-TLP-semisubmersible wind-wave devices.

WEC can be integrated into a wind turbine on the same platform to make the substructure strong; however, a lot of improvements are required to adjust the WECs onto an existing wind turbine. Recently, many researchers have put their efforts to tackle this challenge. For example, Green Ocean Energy is developing the Wave Trader, Danish wave energy is developing the Wave Star and WEGA [8].

A number of industrial companies have also been working on the hybrid floating wind and wave devices. For example, a floating-power plant in Netherland has designed the Poseidon-floating-power while Ocean Wave and Wind Energy Ltd. (OWWE) is designed in Norway. The US Float Inc. has designed the offshore ocean energy system and the US Principle Power Inc. has designed the wind-wave float model. Both models are generating electrical power.

The combined wind and wave energy technologies are also arranged to operate as an island system. The island system combines the hybrid utilization of wind-wave sources on the one island. This system can be classified into two categories: artificial-island and floating-islands. The artificial islands are made by utilizing dykes or a large reef. The most recent work on artificial island system is undertaken by KEMA Energy Island and Dutch DNV KEMA Consulting. A floating island, as another type of island system, is built based on large multipurpose floating platforms. More details about the industrial hybrid wind and wave system are shown in Table 4 and further summarized as follows.

Table 4. The cogeneration pattern and the industry working on HOWWE. Adapted with permission from Ref. [8]. 2015, Elsevier.

Type of the System	Cogeneration Pattern	Companies Name
Co-located	Independent array	WindEurope
	Combined array	
Hybrid	Bottom fixed	WEGA, WaveStar, Wave-Trader
	Floating	OOES, WindWaveFloat, Poseidon, W2Power, OWWE
Island system	Artificial reefs	Kema Energy Island
	Floating	Hexicom, OTEC Energy Island, Hydrogenase

6.1. Bottom Fixed System

The bottom fixed system can be independent or not. For the independent bottom fixed system, the WECs and the wind turbine are deployed in the same platform by sharing the same grid connections [8]. The WECs are distributed as a wave array accordingly in line with the wind turbines. However, the independent bottom fixed system is not a good choice for co-located system designs because of high risk of collision between wind turbine and WECs. For the bottom fixed system, the platform is shared between wind turbine and

WECs; however, there are no wind turbine floating bodies. The cost of the system is also reduced due to the sharing platform and the high yield of energy [96].

6.2. Floating System

Both wind and wave energy converters are floating structures. This option is beneficial because the floating system can float easily on deeper water. The submersible floating systems are categorized as the TLP, barge and spar. The use of barge and TLP has been increased in recent wind-wave structure developments for ultra-deep underwater activities. These systems require the slack mooring system against their instability. The conventional approach was used by FWT, which introduces spar-buoy, TLPs and pontoon type (barge-type).

The barge is a long surface type WEC that uses a huge water plane area and shallow draft to maintain stability. This type of system is well-known in hybrid offshore structures. Spar is another well-known platform used for the floating platform, which is used in a shallow sea. They have a basic layout of legs that are used for buoys and can be used in long term energy production. The use of spar is based on the specific design that allows the use of wind, wave and currents more efficiently. Due to the large diameter of the spar platform, it is built in a vertical cylindrical shape based on a supporting deck, with the bottom being constructed with material that is denser than water, hence allowing to be floating underwater. There are three basic types of the spar: classical, cell and truss spar. Truss spar is used in hard tank configuration with a shorter cylindrical shape, which is different from a classical structure where the truss spar is connected to the bottom. The truss spar structure used in the literature [8] is based on four large orthogonal legs which are separated by X-braces and damping structures between each plane are achieved using heave plates. Immediately after the truss structure, there is the soft keel that allows the housing of heavy blasting material, which is commonly used in the floating systems.

For the large floating systems, the first concept barge was required to maintain the system's stability. The option with a water depth of 80m is to use the semi TLP. The semi type floating system is better than the TLP because the tidal elevation is very sensitive due to tether and buoyancy tensions of the TLP. Semi-floating structure is made based on decks, multi-column, pontoons and bracing members [97], as shown in Figure 6. The connection of columns in the semi-floating structure by using decks and pontoons is supported by the bracing members. On the top of every column, the wind turbine is installed. The WECs are placed between the structure of decks and pontoon. Due to strong wind pressure and strong sea waves on the system, the system reaches the unstable state, which decreases the performance of the system as well as increases the additional operating cost due to damage and fatigue [98].

The International Electro-Technical Commission is working on reviews of the additional maintenance, capital and operation costs for the FWT [99]. It is a challenging task to minimize the operational and maintenance cost, which requires suitable control techniques [100].

7. Synergies and Challenges

Various synergies have been tried to create the integrated HOWWE framework. These efforts have improved energy yield, better consistency, smoothed power supply, shared platform, maintenance, shadow impacts and environmental advantages. The increase in power unit device size and dynamic motion results in the increased output [101]. The integrated framework reduces power fluctuations [102] because of a slacking environment of the wave-energy as compared to the offshore wind [95]. Moreover, the integrated HOWWE brings about a decrease in environmental effects [84], noise [103], visual effects and sea transport. The full-scale integration of HOWWE is still in its initial phase [104–106], which can be improved by applying control algorithms such as super twisting [107]. The environmental effects on the wind-wave turbine are assessed by analyzing the nature of the site area [108]. The deeper water puts many constraints in action, including environmental effects like endangered species and turbulence.

The environmental effects also concern with the collision of birds with wind-wave farms, effects on marine life and disturbance to other life forms; however, with proper precautions and factors analysis, the cautious optimistic approach could alter these situations and ease the overall process. The offshore farms may disturb damagingly the oceanic surroundings with avian collisions, noise [108] and electromagnetic fields [109–111]. Quantitative spatial planning has been the widely used planning methodology so far for the combined HOWWE installations [112]. A new model is developed in [113] based on semi-submersible Nautilus, where the offshore wind turbine is integrated with four-point absorber WECs.

There are challenges in the HOWWE system such as power inversion and platform for power distribution. These challenges might be overcome by using appropriate techniques such as by using PLL based VSI (Voltage source inverter) and multipurpose platform. The flow chart, as shown in Figure 7, could be used for future generated HOWWE system using the individual power conversions and joint inversion. This system presents grid connected combined offshore wind and wave energy systems with power conversion for individual energy sources and shared power inversion of both energy sources. Similarly, power converter mixtures can be utilized in such frameworks in combination of on-location battery storage, thus providing the continuous output supply.

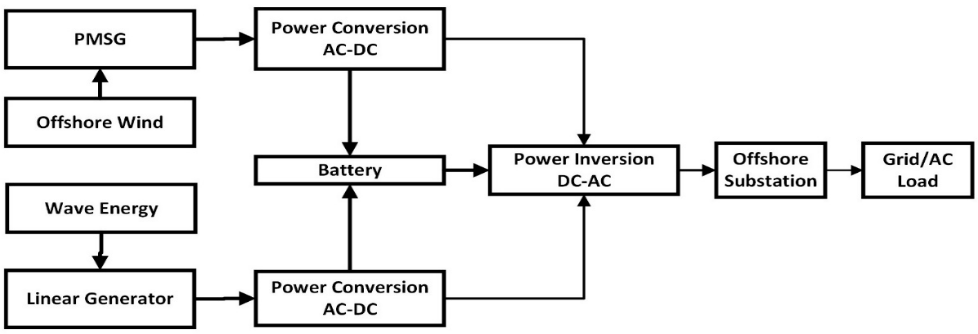

Figure 7. PMSG and linear generator based HOWWE system.

Figure 8 represents a feasible arrangement of conversion framework with an OWT and a WEC with DC energy storage. This arrangement presents AC-DC and DC-AC power conversion with reference to wave energy generation and battery storage units, respectively. The power conversion is carried out by VSC and power inversion is carried out by VSI. Such topologies could improve the systems efficiency of the system in relations of output-power and co-generation cost.

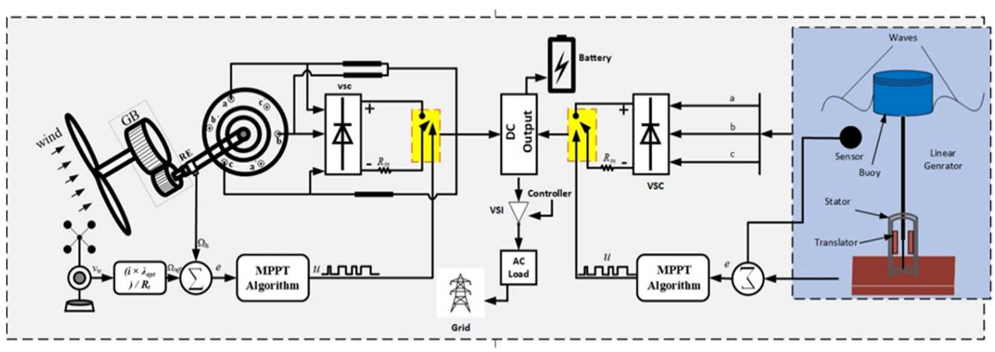

Figure 8. HOWWE with VSC and PLL based VSI.

Multipurpose platform (MPP) is used to fulfil the demands of cogeneration and colocation for the offshore energy resources. MPPs would also endorse an optimization, efficient design, integrated solution and ecological use of sea energy resources through shared platform or infrastructure. MPPs have noteworthy prospective in economizing offshore energy sectors and minimising the operational costs for the offshore wind-wave energy by doing combined spatial planning. The MPP grid is not like conventional grid as the prior relies on a group of power inverters and generators. Control system of every generator offer voltage-frequency regulation. A MPP strategy is consequently essential to deliver the functioning states to the local electrical-control systems to attain network stabilization. The power network-management is established grounded on the size of MPP and interconnection category such as grid-connected or isolated. In [114], different number of MPP schemes are studied, targeting to assign the multidisciplinary feasibility tasks. In [115], a complete assessment of Blue-Growth and MPP are studied; both techniques are studied in strategy plans as along with the comprehensive range of current knowledge being analyzed. While the terms multi-use platform (MUP) and MPP are often used interchangeably, (MUP) is a technqiue to integrate joint maritime economic activities within the close geographical area [116], while MPP refers to a structure capable of developing the synergies between different aquaculture system. A control system of MUP is founded based on frequency/voltage regulation and load control of the wind-wave system. In addition, it is required to tune the network of MUP grid or hybrid offshore wind and wave energy with the main control grid. To deliver the output power efficiently at the system level is also a challenge, which can be improved by using a hierarchical control of HOWWE. This can be made based on three levels: supervisory, central and local controller, with the lower level being local and the highest level being supervisory. The local controllers can be categorized as microcontrollers (MC) and load controllers (LC). The efficiency of HOWWE farms is thus improved by power linking of offshore wind and wave array, based on the layout of both HOWWE and local grid arrangement.

8. Conclusions

This review paper has offered a main analysis of the most related aspects linked to the combined HOWWE systems. An extensive review of the different control concepts related to wind-wave systems is presented. This study has focused on the power conversion and advanced control coupling implementation of HOWWE systems. A straightforward choice at the present phase for improvement of HOWWE technologies is the co-located systems by merging the OWT with a WEC array. The power can be optimized with different control techniques for the PMSG and linear generator for HOWWE, respectively. The power output can also be optimized based on the different power conversion system such as VSC and VSI with HVDC transmission. By comparing both wind and wave operation and the design, it is found that the control design and structural load reduction are important for the system to be able to maximize the power output while keeping stability. Furthermore, the coupling between the winds and waves is crucial for the site colocation, in order to achieve the efficient energy generation from both energy resources. This review paper provides closely-relevant knowledge of the HOWWE system. Considerable research is required in control designs, efficient power conversion and reliable grid integration to harness power from the integrated HOWWE system.

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